Single-Frequency, Narrow-Linewidth Distributed Feedback Waveguide Laser in $Al_2O_3:Er^{3+}$ on Silicon

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***Abstract*—A distributed feedback channel waveguide laser in erbium-doped aluminum oxide on a silicon substrate is reported. The optically pumped laser has a threshold pump power of 15 mW and emits 3 mW in single-frequency operation at 1545.2 nm wavelength with a slope efficiency of 6.2% and linewidth of 15 kHz.**

***Keywords*—Distributed feedback (DFB) laser; waveguide laser; erbium-doped laser; Bragg gratings; aluminum oxide**

I. Introduction

Dense wavelength division multiplexing (DWDM) in telecommunication networks has been one of the main driving forces behind the development of single-frequency lasers operating in the telecommunication C-band (1530-1565 nm). Monolithic erbium-doped dielectric distributed feedback (DFB) waveguide lasers are of particular interest for this application due to their stable, single-mode, single-polarization, extremely narrow-linewidth and low-noise emission [1,2].

Erbium-doped aluminum oxide ($Al_2O_3:Er^{3+}$) has been identified as a very promising gain medium to realize such integrated single-frequency waveguide lasers due to its favorable optical properties and compatibility with existing silicon waveguide technology. $Al_2O_3:Er^{3+}$ waveguides with low propagation losses and an internal optical gain over an 80 nm wavelength range, by far exceeding the range of the telecommunication C-band, with a peak gain of 2.0 dB/cm have recently been realized [3]. The first $Al_2O_3:Er^{3+}$ integrated waveguide laser was consequently demonstrated soon thereafter [4].

In this work we present the first monolithic single-frequency distributed feedback channel waveguide laser in $Al_2O_3:Er^{3+}$. Its output power is in the milliwatt range, with a low pump threshold and high slope efficiency being achieved due to tight light confinement and small propagation losses in our channel waveguides, while also providing the additional feature of single-frequency, narrow-linewidth operation. The laser power and spectral characteristics make it an excellent competitor against well-established optical waveguide technologies such as erbium-doped phosphate glass and lithium niobate channel waveguide lasers [1,2,5].

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II. Fabrication

The channel waveguides were fabricated in $Al_2O_3:Er^{3+}$ layers which were deposited onto standard thermally oxidized silicon wafers [6]. The erbium doping concentration has been set to $\sim 3\times 10^{20}$ cm^{-3}. The ridge waveguides were 1 cm long, 3 µm wide and were etched 0.1 µm deep via a reactive ion etching process [7]. The waveguide geometry was designed to support only single transverse-mode operation at the pump and laser wavelengths. A 650-nm-thick plasma-enhanced chemical vapor deposition (PECVD) SiO_2 cladding layer was deposited on top of the ridge waveguides.

Optical feedback in the cavity was provided by a 1-cm-long surface relief Bragg grating. The grating pattern was defined in a 120-nm-thick negative resist layer on top of the SiO_2 by means of laser interference lithography (LIL). Finally, the grating pattern was etched into the SiO_2 layer using a $CHF_3:O_2$ reactive ion plasma, after which the residual resist was removed by an O_2 plasma. The resultant Bragg grating had an etch depth of ~150 nm with a period of 488 nm and a duty cycle of ~50%. In order to ensure single longitudinal mode operation, a distributed quarter-wave phase shift was introduced to the cavity by means of a 2-mm-long adiabatic sinusoidal tapering of the waveguide width in the center region of the cavity [8].

III. Characterization

The laser was optically pumped by a 1480 nm laser diode where a maximum pump power of 67 mW was launched into the waveguide via a 1480/1550 nm wavelength division multiplexing (WDM) fiber. The laser emission was collected from the pumped side of the cavity with the WDM fiber and sent to a power meter. The power characteristic of the laser is shown in Fig. 1. The DFB laser threshold occurs at a launched pump power of 15 mW. The maximum laser emission from the pumped side of the cavity is more than 3 mW, which results in a slope efficiency of 6.2% versus launched pump power. The unabsorbed pump power that was collected at the unpumped side of the cavity indicated that only approximately 20% of the launched pump power is absorbed in the cavity so that a pump power threshold of below 3 mW and slope efficiency of more than 30% are

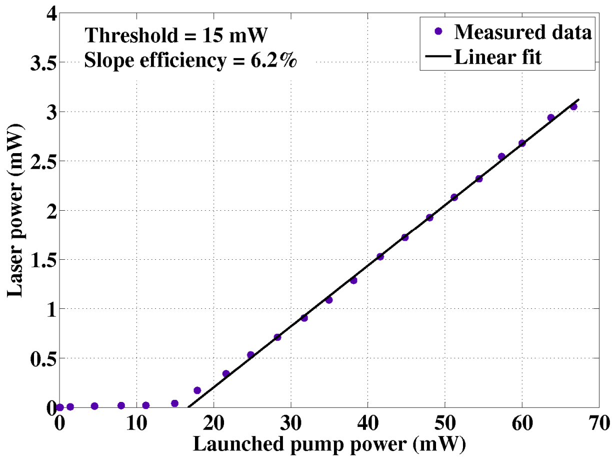

Figure 1. Laser output power laser as a function of launched pump power

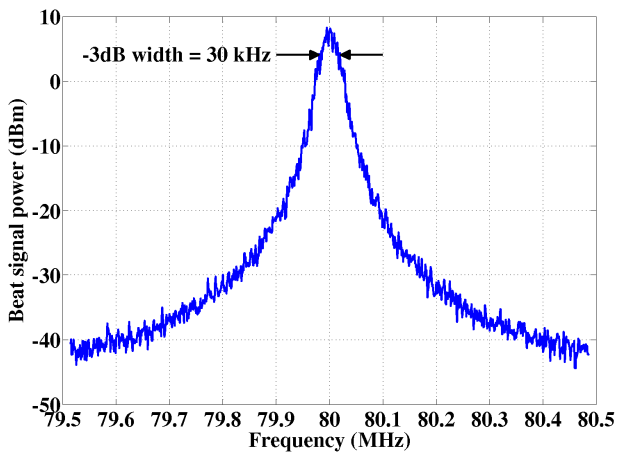

Figure 2. The heterodyne RF beat signal with a –3dB linewidth of 30 kHz

derived versus absorbed pump power. The low threshold is a consequence of the strong light confinement due to the comparatively high refractive index of Al_2O_3 of ~1.65 which allows the fabrication of compact integrated optical structures and small waveguide cross-sections.

The laser emission from the unpumped side of the cavity was collected with a WDM fiber and sent to an optical spectrum analyzer (OSA) with a resolution of 0.1 nm. The laser operated at a wavelength of 1545.2 nm (TE polarized) and the single emission peak is more than 40 dB above the amplified spontaneous emission noise floor. Since characterization of the Bragg gratings showed that the Bragg reflection of the TM mode occurs at ~1533 nm, we conclude that the laser was operating TE-polarized at all times. Although single-mode behavior could be confirmed with the OSA measurement, the linewidth of the laser emission was limited by the resolution of the OSA.

Consequently a delayed self-heterodyne interferometer with a much higher resolution of ~10 kHz was implemented to measure the laser linewidth [9]. The setup was constructed with two 50/50 couplers, a 9.5 km fiber, an 80 MHz acousto-optic modulator, photo-detector and an RF spectrum analyzer. The measured –3 dB linewidth of the beated RF signal was 30 kHz, which implies a laser linewidth of 15 kHz for a Lorentzian lineshape (Fig. 2). We believe that the actual laser linewidth is in fact significantly narrower and that the current measured value for the linewidth is a result of excessive noise in the heterodyning measurement setup. We are currently in the process of extending the heterodyne interferometer to a recirculating delayed self-heterodyne interferometer which will reduce the linewidth resolution of the setup to the sub-kilohertz regime. Additionally we are also addressing the issue of excessive noise in the measurement setup.

IV. CONCLUSION

A monolithic distributed-feedback waveguide laser in $Al_2O_3:Er^{3+}$ was presented. The low-threshold laser demonstrated narrow-linewidth, single-longitudinal-mode, and single-polarization emission. A maximum output power of more than 3 mW was achieved with a linewidth of <15 kHz. To the best of our knowledge, this is the first rare-earth-ion-doped DFB laser that is fabricated on a silicon substrate. This result holds many promising opportunities for the integration of such single-frequency lasers with existing dielectric waveguide technology on silicon substrates.

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